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documents filed in connection with the following patent
application:

Application No. 2003/0144

Date of Filing 28 February 2003

Applicant DUBLIN CITY UNIVERSITY, a Statutory Body
Corporate established under Irish law of Glasnevin,
Dublin 9, Ireland.

Dated this 16 day of March 2004.



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APPLICATION NO.

Form No.1

REQUEST FOR THE GRANT OF A PATENT

Patents Act, 1992

The Applicant(s) named herein hereby request(s)

☒ the grant of a patent under Part II of the Act

the grant of a short term patent under Part III of the Act on the basis of the information furnished hereunder

1. Applicant(s)

Name: DUBLIN CITY UNIVERSITY

Address: Glasnevin, Dublin 9, Ireland

Description/Nationality: a Statutory Body Corporate established under Irish law

2. Title of Invention:

IMPROVED OPTICAL SENSORS

3. Declaration of Priority on basis of previously filed application(s) for same invention (Sections 25 & 26)

Previous Filing Date

Country in or for which filed

Filing No.

4. Identification of Inventor(s):

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5. Statement of right to be granted a patent (Section 17(2) (b))

Date of assignment from inventors: 28th February 2003

6. Items accompanying this Request - tick as appropriate

- (i) ☒ prescribed filing fee
- (ii) ☒ specification containing a description and claims
☒ specification containing a description only
☒ Drawings to be referred to in description or claims

- (iii) An abstract
- (iv) Copy of previous application(s) whose priority is claimed
- (v) Translation of previous application whose priority is claimed
- (vi) ☒ Authorisation of Agent (this may be given at 8 below if this request is signed by the applicant(s))

7. Divisional Application(s)

The following is applicable to the present application which is made under Section 24 -

Earlier Application No:
Filing Date:

8. Agent

The following is authorised to act as agent in all proceedings connected with the obtaining of a patent to which this request relates and in relation to any patent granted.-

Name

Address

TOMKINS & CO.

**5 Dartmouth Road,
Dublin 6.**

9. Address for Service (if different from that at 8)

TOMKINS & CO., at their address as recorded for the time being in the Register of Patent Agents.

Signed

Name(s):
by:

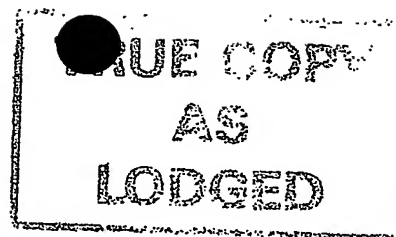
Capacity (if the applicant is a body corporate):

Date: 28 February 2003

AUTO5315

Title of the Invention

Improved Optical Sensors



5 Field of the Invention

The present invention relates to an improved carbon dioxide sensor, to combined carbon dioxide sensor, to methods of making the sensors, to the use of such sensors and to methods of applying the sensors onto a substrate.

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Background of the Invention

Carbon dioxide (CO₂) sensors are already known. For example, WO 99/06821 discloses a method and device for the fluorometric determination of a biological, chemical or physical parameter of a sample, using at least two different luminescent materials, the first of which responds to the parameter at least as regards luminescence intensity and the second of which does not respond to the parameter as regards luminescence intensity and decay time. The luminescent materials have different decay times and the time or phase behaviour of the luminescence response obtained is used to generate a reference variable for determining a parameter. This Dual Luminophore Referencing (DLR) is an internal ratiometric method whereby the analyte-sensitive fluorescence intensity signal is converted into the phase domain by co-immobilizing an inert long-lifetime reference luminophore with similar spectral characteristics. Generally speaking a long-lived phosphor is immobilized in a sol-gel and then formed into sintered glass. The sintered glass and a short-lived phosphor are then formed into a polymer matrix with a polymer such as ethyl cellulose polymer.

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One problem associated with this type of sensor is that because the sensor is formulated in a polymer matrix, the polymer will swell in a moist environment, which affects the calibration of the sensor and makes the sensor less reliable in moist environments. Furthermore, mechanical strength of a polymer is low in that the material is a rubbery type material rather than a rigid glass-like material like sol-gel, and optical transparency can be poor as polymeric films can be cloudy.

The sensors of the present invention find application in the packaging industry and in particular in areas where the applications require a guarantee of the integrity of the package. Such packages include food packaging in general, and specifically of food exports, particularly of high margin foods e.g. certain fish / shellfish, bulk food ingredients, wine, beer, long term food storage as required for emergency aid and military operations, in the catering industry, pharmaceutical industry and in the packaging of medical disposables, surgical instruments and paediatric products as well as in any sectors that required a clean room manufacturing or assembly environment.

Currently used methods of checking the integrity of packages and the possible contamination of sterilised products involve destructive sampling in which a proportion of the packages are opened and tested for damage to the packaging for microbial contamination. However, this method only tests a small proportion of the packages and damaged packages could be present in the much larger proportion of packages not tested. Furthermore, the method destroys packages which may well have been intact and is therefore quite wasteful of both packages and their contents.

Food products are often packed under a protective atmosphere of carbon dioxide. Often, but not always, the exclusion of oxygen is preferred in order to inhibit growth of aerobic spoilage organisms, whereas carbon dioxide is typically used to decrease bacterial growth rates. Because package integrity is an essential requirement for the quality of MAP food, leakage detection is a very important part of MAP technology. The standard method currently used to check the integrity of the modified atmosphere package (MAP) involves the use of a MAP analyser instrument. This involves piecing the package using a needle probe to withdraw a sample of the protective gas atmosphere. The gas is then analysed using an electrochemical sensor to determine the oxygen concentration, and infrared spectrometry to determine the carbon dioxide concentration. As this is a destructive method, only a small percentage of the packages can be tested and so 100% quality control is not possible. Testing normally takes place at the packaging plant and is a validation of the packaging process. If a package is found to be leaking, what follows is a time consuming and costly process of back-checking and repacking. Once the packages

leave the processing plant, there is no monitoring of the package integrity or freshness of the food (e.g. PBI-Dansensor *MAP Check Combi* or Systech Interuments *Portamap2* or *Gaspac*).

5 Another instrument used to check for leak detection uses non-invasive methods. This involves placing the package into a pressure chamber and checking for leaks using carbon dioxide. It has the advantage of being non-destructive but is time-consuming and would not easily be incorporated into a production line. (e.g. PBI-Dansensor *Pack Check*).

10

An optical sensor for oxygen detection has been commercialised recently. It is based on fluorescence lifetime detection of a Ruthenium dye complex. This technology has been developed by DecisionLink in conjunction with the Sensor Development Department of TNO Voeding, and is being marketed as a *Non-Invasive Oxygen Analyser for Food and Beverage Applications*. The ruthenium dye is immobilised in a polymer matrix, and the detection method uses a time gated measurement with excitation by a pulsed LED. The sensor film is an adhesive sticker stuck onto the inside of the package or jar. The instrument consists of a small box containing the light source, detector and fibre reader pen and is connected to a PC. (DecisionLink *OxySense*). The problem with this sensor is that it only measures oxygen levels, when in fact it is normally a fall in O₂ levels and a concomitant rise in CO₂ levels which is indicative of microbial spoilage. Additionally, the sticker, which is in contact with the package contents, could become unstuck and possibly damage or otherwise interfere with the contents.

25

Many of the optical-based sensors for food packaging that have been made available are visual indicators in the form of inserts that also contain scavenging capability, and are not very accurate.

30 **Object of the invention**

It is thus an object of the present invention to provide a sensor which is less sensitive to the moisture content of the environment, which can tolerate moderate

fluctuations in the moisture content of the environment and which has a reliable calibration range over a range of moisture levels.

It is a further object to provide a CO₂ sensor which is substantially insensitive to O₂ levels under normal working conditions. It is also an object to provide a sensor which allows for the combined measurement of CO₂ and O₂ levels. It is also an object to provide an optically readable sensor for CO₂.

A further object of the invention is to provide a quality control method and a sensor for use in the method, for checking the integrity and hence microbial contamination of packaging, in a non-destructive manner. The invention also seeks to provide a packaging medium which incorporates a sensor which allows the integrity and level of microbial contamination of the package and its contents to be assessed. It is also an object of the invention to provide a quality control method which allows all of the manufacturer the possibility of checking each package i.e. 100% quality control and validation of modified atmosphere packaging process, and the retailer and the consumer the possibility of checking packages when they arrive at the retail outlet, on the shelves, at the purchase point so that the consumer can be secure in the knowledge that the food is fresh.

Summary of the invention

According to the present invention there is provided a CO₂ sensor comprising a pH indicator and a long-lived reference luminophore which are co-immobilised in a porous sol-gel matrix. Long-lived luminophore in this case means one that has a lifetime/decaytime long enough to be measured using low-cost instrumentation. In the case of this indicator, the unquenched decaytime is approx 5 μ s.

The pH indicator may be hydroxypyrene trisulphonate (HPTS). Other suitable pH indicators include fluorescein, m-cresol purple, thymol blue, phenol red, xylenol blue. HPTS is advantageous due to its spectral compatibility with the long-lived ruthenium reference indicator, its pK_a value (~7.3), its good photostability and high quantum yield.

The long-lived reference luminophore may be ruthenium-doped sol-gel microparticles. The ruthenium dopant in the sol-gel microparticles may be $[\text{Ru}^{\text{II}}\text{-tris(4,7-diphenyl-1,10-phenanthroline)}]\text{Cl}_2$. Other suitable compounds are any Ruthenium-based compounds with α -diimine ligands or any luminescent transition metal complexes with platinum metals Ru, Os, Pt, Ir, Re or Rh as the central metal atom and α -diimine ligands, or phosphorescent porphyrins with Pt or Pd as the central metal atom.

The porous sol-gel matrix may be a methyltriethoxysilane (MTEOS) sol-gel matrix. Also suitable are other hybrid (organic-inorganic) sol-gel matrices such as ethyltriethoxysilane (ETEOS), phenyltriethoxysilane (PhTEOS) and methyltrimethoxysilane (MTMS).

In another aspect the invention provides a combined O_2 / CO_2 sensor comprising:-

- (a) an O_2 sensor comprising an oxygen sensitive ruthenium complex,
- (b) immobilised in a porous sol-gel matrix, and
- (c) an CO_2 sensor comprising a pH indicator and a long-lived reference luminophore which are co-immobilised in a porous sol-gel matrix.

Suitable ruthenium complexes include those ruthenium-based compounds with α -diimine ligands and luminescent transition metal complexes with platinum metals (Ru, Os, Pt, Ir, Re or Rh) as the central metal atom with α -diimine ligands, and phosphorescent porphyrins with Pt or Pd as the central metal atom.

The combined sensor may further comprise the immobilised O_2 sensor and the immobilised CO_2 sensor being coated onto the same substrate. Preferably, the two sensors are coated onto the substrate side-by-side. The substrate may be a layer of plastics material, including surface-enhanced PET and PET/PE laminates or glass or any rigid substrate materials such as Perspex/PMMA, polycarbonate, or any flexible substrate material such as acetate (transparent foils for overhead projector) or flexible polymer materials.

In a still further aspect the invention provides a method of making a CO₂ sensor comprising :-

(1) synthesis of an Ru(dpp)₃(TSPS)₂ ion-pair comprising mixing dissolved Ru(dpp)₃Cl₂ with trimethylsilylpropane sulfonic acid, sodium salt and allowing the ion-pair to precipitate,

(2) synthesis of the particles comprising condensing the dissolved Ru(dpp)₃(TSPS)₂ ion-pair with TEOS and halting the condensation reaction with alcohol, washing the condensate with alcohol and drying the condensate,

(3) and fabrication of the CO₂ sensor films comprising suspending the doped reference particles in the coimmobilisation matrix solution, mixing the coimmobilisation matrix solution into a pH indicator solution which comprises a pH indicator in a quaternary ammonium hydroxide solution, and saturating the mixture immediately with CO₂ followed by deposition onto a substrate.

The quaternary ammonium hydroxide solution may be cetyl-trimetyl ammonium hydroxide (CTA-OH), tetra-octyl ammonium hydroxide (TOA-OH) or tetra-butyl ammonium hydroxide (TBA-OH) or other quaternary ammonium hydroxides.

The invention also provides a packaging medium having a CO₂ sensor and an O₂ sensor as defined above formed on a surface of the medium which will lie internally of the package when the package is formed. The sensors may be formed on the packaging medium by dip-coating, spin-coating, spray-coating, stamp-printing, screen-printing, ink-jet printing or Gravure printing.

The invention also provides a quality control method comprising reading a combined O₂ /CO₂ sensor as defined above, formed on the internal surface of a package, with an optical reader and determining the levels of O₂ and CO₂ inside the package in relation to a control, a rise in O₂ level and a corresponding fall in CO₂ level indicating contamination of the package.

The optical reader comprises a probe that measures approximately 15 cm in length with a diameter of 4 cm. There are two LEDs; the first is the excitation source and the second is the reference. The excitation source is a blue LED (Nichia, NSPB500) and is chosen for its relatively stable temperature characteristics which match those of the

reference LED. The detector is a silicon photodiode (Hamamatsu, S1223), which also exhibits good temperature stability. Modulated light from the blue LED is filtered using a blue glass bandpass filter (OF1: Schott, BG12) of thickness 2mm in order to eliminate the high wavelength tail of the LED emission. The phase-shifted

5 fluorescence from the sensor film is incident on the photodiode after passing through an optical long-pass filter (OF3: LEE-gel filter 135), to separate the excitation light from the emission. The second LED (Hewlett Packard, HLMA-KL00) is part of an internal dual referencing scheme. This reference LED emits at 590nm and is filtered by a bandpass filter (OF3: Schott, BG39). This LED is in the same spectral range as
10 the fluorescence (610nm), and has been carefully selected to match the blue excitation LED in terms of switching time and temperature characteristics. Spurious phase shifts as a function of temperature and other fluctuations are eliminated by this dual referencing. The detection electronics measure the variation in phase angle with oxygen or carbon dioxide concentration. The phase angle is the measured phase
15 difference between the sinusoidally modulated reference excitation signal and the resultant fluorescence signal which is phase shifted with respect to the reference signal. The fluorescence signal changes with analyte concentration. The phase signals (reference and excitation) are fed into a phase detector and the phase difference is measured.

20 Also provided is a method of screen-printing a combined O_2/CO_2 sensor as defined above onto a plastics substrate comprising forcing the sensor sol through a mask or mesh and drying the substrate. Preferably the substrate is dried at about $80^{\circ}C$ for about 10 min.

25 Also provided is a method of ink-jet printing a combined O_2/CO_2 sensor as defined above onto a plastics substrate comprising filling an ink-jet printer cartridge with sensor sol and printing the sensor sol onto the substrate using an ink-jet printer.

30 **Brief description of the drawings**

Figure 1 is a digital image of Ru-doped MTEOS films screen-printed onto PET under blue LED excitation with a red filter,

Figure 2: Single sine wave signals generated by the reference luminophore (Reference) and the analyte-sensitive luminophore (HPTS). The superposition of the two signals represents the detected signal (Total Signal),

5 **Figure 3:** Schematic of experimental system used to measure the oxygen and carbon dioxide sensitivity of the sensor films,

Figure 4: Calibration data for CO₂ sensor using N₂ as carrier gas for the first cycle, and air as carrier gas for the second cycle,

10

Figure 5: Oxygen calibration data from screen printed films, and

Figure 6: Ink-jet printed oxygen sensor films on acetate substrate

15 Detailed description of the Invention

Optical sensor films with associated scanner to confirm the integrity of the package and hence freshness of packaged food in a non-destructive manner. Sensor films have been developed for oxygen and carbon dioxide. They are
20 fluorescent and their fluorescence changes with exposure to the specific gas concentration. The films can be deposited on a solid or a flexible substrate using standard printing techniques e.g. spin coating, screen printing etc. The films are excited by a common excitation source i.e. a blue LED, and the resultant fluorescence is detected using a silicon photodiode. These optoelectronic components along with
25 relevant ICs and electronic components can be housed in a scanner device capable of interrogating the sensor films.

Fluorescent sensors for oxygen and carbon dioxide have been developed. Both of these sensors can be scanned using an optical reader, which will give a
30 readout of the concentration of oxygen and carbon dioxide in the package using non-destructive methods. This will enable 100% quality control from the packaging plant to the consumer purchase point.

Oxygen sensor formulation: It is based on an oxygen-sensitive dye complex, [Ru-tris(4,7-diphenyl-1,10-phenanthroline)]Cl₂, immobilised in a porous hybrid sol-gel matrix. The oxygen gas can diffuse through the matrix and quench (reduce) the intensity and decay-time of the fluorescence from the dye complex. The preferred method of detection monitors the decay-time of the indicator, hence detection is in the time domain and uses low-cost instrumentation. As the oxygen concentration increases, the intensity/decay-time decreases. The formulation can be deposited/printed onto a support matrix – in the case of the intelligent packaging application, the sensor film is deposited onto a flexible packaging material.

Carbon dioxide formulation: This sensor is more complex than the oxygen sensor, and uses a technique known as Dual Luminophore Referencing (DLR) [Ger. Pat. Appl., DE 198.29.657, 1997]. This technique enables CO₂ sensing of a short-lived indicator in the time domain using low-cost instrumentation. Carbon dioxide sensing exploits the acidic nature of the gas. Most reported fluorescence-based optical carbon dioxide sensors rely on the intensity change of a luminescent pH indicator such as 1-hydroxypyrene-3,6,8-trisulfonate (HPTS), but the very short decay times of such species cannot be measured by the low-cost phase modulation techniques used for oxygen sensors. The present invention offers the possibility of an optical sensing scheme for CO₂, which is compatible with that for oxygen. In the CO₂ sensor, [Ru(dpp)₃]Cl₂, used above for the oxygen sensor, is used as the reference luminophore in the DLR-based CO₂ sensor strip. Excitation and emission wavelengths of ruthenium complexes and the HPTS dye are sufficiently well matched to make them excellent candidates for a DLR-type carbon dioxide sensor and the use of the same ruthenium complex in the oxygen sensor strip, ensures excellent cross compatibility between the two sensors, enabling the use of a single optical read-out device in the food packaging application. Due to the extremely good quenchability by molecular oxygen of the ruthenium complex used as the reference in the CO₂ sensor strip, the dye is incorporated in sol-gel microparticles, to minimize oxygen cross-sensitivity. These microparticles are fabricated using the sol-gel process with TEOS as precursor. These particles are sensitive to oxygen, but when they are immobilized in the MTEOS sol, that they are no longer oxygen-sensitive.

1. Fabrication process

1.1 Synthesis of O₂ sensor

O₂ sensor is composed of an oxygen-sensitive complex, Ru- tris(4,7 -diphenyl-1,10-phenanthroline)²⁺ immobilised in a porous sol-gel matrix. The silicon alkoxide precursor, methyltriethoxysilane (MTEOS) is mixed with water at pH 1 (using HCl as catalyst) and ethanol as co-solvent. The MTEOS to water ratio used is 4:1. The ruthenium complex is added to the precursor solution and the mixture stirred for 1 h. The typical concentration of the ruthenium complex used is 2.5 g/L with respect to the precursor solution. After stirring for one hour, the sol is used to coat the substrates or supports onto which the sensor material is deposited e.g. Glass, PMMA, Flexible packaging material, acetate etc

1.2 Synthesis of CO₂ sensor

CO₂ sensor is composed of a pH indicator, hydroxypyrene trisulphonate, HPTS, (exploiting the acidic nature of the CO₂ gas i.e. CO₂ is converted to carbonic acid in the presence of water) and a long-lived reference luminophore, ruthenium-doped sol-gel microparticles, co-immobilised in a porous (MTEOS) sol-gel matrix. The production of the CO₂ sensor films is structured in three phases: synthesis of the Ru(dpp)₃(TSPS)₂ ion-pair, synthesis of the particles and fabrication of the CO₂ membranes.

(a.) Synthesis of Ru(dpp)₃(TSPS)₂:

Dissolve 400 mg Ru(dpp)₃Cl₂ in 70 ml of a 10/4 mixture acetone/ethanol.

Add 50 ml of H₂O and filter.

Add a filtered solution of 218.3 mg trimethylsilylpropane sulfonic acid, sodium salt (Na-TSPS) in 50 ml deionised H₂O and filter the mixture again.

Let stand until the mixture is evaporated down to 70 – 100 ml and the ion-pair has precipitated. This normally takes a couple of days, or overnight in the fume hood.

Filter and wash with plenty of water.

Weigh after drying at 70°C.

(b.) Synthesis of the TEOS μ -particles:

Dissolve 380 mg of the Ru(dpp)₃(TSPS)₂ ion-pair in 23.05 ml of acetic acid (HOAc) and add 7.25 ml of deionised H₂O.

Add 22.45 ml of TEOS and stir for 90 seconds. Switch stirrer off and let the solution stand for a further 13.5 minutes, during which it will start to turn opaque (formation of a suspension).

Add 50 ml of ethanol (EtOH) to stop the condensation reaction and let the suspension stand for 30 minutes.

Filter (keep the filtrate and do not add acetone to it) and wash with acetone, until the washing liquid is colourless.

Dry at 70°C for three days, grind the crusted particles in the mortar and weigh: 1.539 g of a lightly orange coloured very fine powder

(c.) Membrane preparation:

Prepare CTA-OH solution: stir 1.432 g CTA-Br and 0.911 g AgO over 6 ml MeOH for 2 h, then filter with a PTFE filter.

Suspend 160 mg of the doped particles in 4.0 ml MTEOS, add 1.45 ml of 0.1 M HCl and stir for 2 h.

In a second vial, dissolve 30 mg HPTS in 5 ml of the freshly prepared CTA-OH solution

Pour the MTEOS mixture into the HPTS solution and saturate the mixture immediately with CO₂, by bubbling a stream of 100 % CO₂ through it for about two minutes.

Spin-coat the cocktail onto a PE substrate using 1000 RPM spin speed. The substrate should be already spinning when the cocktail (~ 2 ml) is applied to it. Make sure that the cocktail is well mixed before spin-coating, so the particles do not sediment on the bottom of the vial.

Dry the substrates at 70°C for four days, then store in a moist atmosphere.

2. Printing process (screen printing and ink-jet printing)

The standard lab deposition/printing techniques are: dip-coating, spin-coating, spray coating and stamp printing. However for the food packaging application, an industrial-scale printing technique is necessary. For this reason the possibility of printing doped sol-gels was investigated, using both screen printing and ink-jet printing using a standard desktop printer and cartridge.

2.1 *Screen printing* involves forcing the 'ink' (oxygen sensor sol) through a mask/mesh containing the design using a 'squeegee' (a spongy wiper) and printing the desired design on the substrate positioned below the mask. Once printed the substrate was then dried as it was moved through a horizontal four-chamber oven at 80 degrees C for 10 minutes. The mask used for the screen-printing trials consists of a series of lines of different widths and separations as can be seen in Figure 1. Two different substrates were used (both flexible). The first was the standard surface-enhanced PET (50 µm HSPL), and the second was a specialised packaging material (Dyno AF320, Polimoon, U.K.) that is compatible with a conventional Modified Atmosphere Packaging (MAP) instrument. This packaging material is a laminate consisting of PET/PE with an antifog layer.

Overall the screen printing trials were successful using the oxygen sensor sol. Some of the issues encountered with this process were associated with the viscosity of the sol. Normally, high viscosity inks (of the order of thousands of cP) are used for screen printing. Our sensor ink has a very low viscosity (approx 2cP); which results in fast evaporation of the solvent and consequent drying leading to high losses of materials and clogging of the mask. Adhesion of the printed film to the anti-fog layer on the packaging material was found to be a problem, but was very good when the films were printed on the surface-enhanced PET material. Data on the oxygen sensitivity of the screen printed films can be seen in Figure 5.

2.2 *Ink-jet printing* trials were carried out using a standard HP ink-jet printer (HP DESKJET 920C). A cartridge was filled with oxygen sensor sol. The viscosity of the sol is well suited to this technique, as the optimum viscosity of inks for use in ink-jet printing is between 2 and 5 cP. A series of lines of sensor were printed onto both paper and acetate. The quality of the films and adhesion to the acetate was very good. The oxygen sensitivity of the ink-jet printed films can be seen in Fig 6. Text and logos were printed using the oxygen-sensitive sol which clearly demonstrates the versatility of this technique.

3. Measurement/testing process

3.1 A phase fluorometric approach is used in the measurement of the oxygen sensor, which involves operating in the time domain. If the excitation signal is sinusoidally modulated, the dye fluorescence is also modulated but is time delayed or phase shifted relative to the excitation signal. The relationship between the lifetime, τ , and the corresponding phase shift, ϕ , for a single exponential decay, is

$$\tau = \frac{\tan \phi}{2\pi f} \quad (1.)$$

where f is the modulation frequency.

3.2 Dual Luminophore Referencing is a sensing technique used by us to measure carbon dioxide. It enables the conversion of the analyte-sensitive fluorescence intensity signal to the time domain by co-immobilising the analyte-sensitive indicator (pH indicator, HPTS) with an inert long-lifetime reference luminophore (ruthenium-doped sol-gel microparticles) with similar spectral characteristics. Two different luminescence signals are generated in the sensing membrane (see Figure 2). The total signal amplitude (in red) is a superposition of the two signals generated by the analyte-sensitive fluorophore (HPTS - black) and the inert reference luminophore (Reference - Blue). The HPTS signal has a phase angle, $\phi_{\text{sig}} \approx 0$ due to its very short lifetime, and the inert reference signal has a constant amplitude and phase angle, ϕ_{ref} , determined by the modulation frequency and its decay time. The superposition of the two signals will result in a non-zero phase angle, ϕ_m , of the total measured signal. When the HPTS changes its amplitude due to the presence or absence of carbon dioxide, the phase angle ϕ_m will change accordingly, thus ϕ_m can be correlated with the HPTS fluorescence intensity. A theoretical analysis of the process shows that $\cot \phi_m$ is linearly dependent on the amplitude ratio of the two signals $A_{\text{HPTS}}/A_{\text{REF}}$, thereby referencing out any drifts that might occur due to power fluctuations or temperature changes.

3.3 Characterisation system

Figure 3 shows the characterisation system used to measure the sensitivity of the sensor films.

5 A digital dual-phase lock-in amplifier (DSP 7225 Perkin Elmer Instruments, USA) was used for sinusoidal modulation of the LED (20 kHz / 5.0 V) and for phase-shift detection of the photodiode output signal. The optical set-up consisted of a blue LED ($\lambda_{\text{max}} = 470 \text{ nm}$, NSPB 500 Nichia, Germany) with a blue band-pass filter (BG-12, Schott, Mainz, Germany) and an integrated photodiode amplifier (IPL 10530 DAL, IPL Inc, Dorset, UK) with an orange long-pass filter (LEE 135, LEE Filters, Hampshire, UK).

15 For testing the carbon dioxide sensor, the desired concentrations of carbon dioxide were adjusted by mixing pure gases (carbon dioxide and nitrogen) with computer-controlled mass flow controllers (UNIT Instruments, Dublin, Ireland). The gas mixture was humidified using two midjet impingers (to duplicate the humid atmosphere in a modified atmosphere package) and the flow rate was kept constant at $500 \text{ cm}^3 \cdot \text{min}^{-1}$. A similar set-up was used to achieve calibrated oxygen concentrations.

4. Sensing mechanisms

4.1 Oxygen sensing mechanism:

25 The oxygen sensing mechanism involves fluorescence quenching. This refers to any process which decreases the fluorescence intensity (or lifetime) of a given substance. In this work, we are concerned primarily with quenching resulting from collisional encounters between the fluorophore and the quencher (in this case oxygen) called collisional quenching. In this case, the quencher must diffuse to the fluorophore during the lifetime of the excited state. Upon contact, the fluorophore returns to the ground state without emission of a photon. The observed decay is composed of both
30 radiative and non-radiative decay. As the concentration of quencher increases, the non-radiative decay increases, and thus the observed lifetime will decrease with

accompanying decrease in fluorescence intensity. Collisional quenching of fluorescence is described by the Stern-Volmer equation:

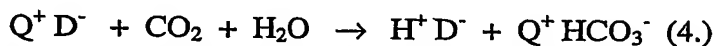
$$\frac{I_0}{I} = 1 + k \tau_0 [Q] = 1 + K_{SV} [Q] \quad (2.)$$

$$\frac{\tau_0}{\tau} = 1 + k \tau_0 [Q] = 1 + K_{SV} [Q] \quad (3.)$$

where I_0 and I are the fluorescence intensities in the absence and presence of quencher, respectively, $[Q]$ is the concentration of quencher, τ_0 and τ are the fluorescence lifetimes in the absence and presence of quencher, respectively, and K_{SV} is the Stern-Volmer quenching constant. In this work, the ruthenium dye complex is the fluorophore and oxygen is the quencher.

4.2 Carbon dioxide sensing mechanism:

Optical CO_2 sensing is normally achieved indirectly by exploiting the acidic nature of the gas. As a result, pH-indicator dyes can be used. In this work, a fluorescence approach is used in order to be compatible with the oxygen sensing scheme. The equation shown below (Eqn. 4) shows the sensing chemistry involved in the carbon dioxide sensor:



where D^- is a pH-indicator dye and Q^+ is the counterion. This mechanism takes advantage of the acidic nature of the carbon dioxide gas (converted to carbonic acid in the presence of water), and monitors the concentration of CO_2 gas via the pH change it induces. Using the aforementioned DLR scheme, HPTS (pH indicator) and Ru-doped microparticles (reference) co-immobilised in a sol-gel matrix, the fluorescence intensity signal generated by the HPTS is converted to the time domain giving a phase signal compatible with that of the oxygen sensor. This formulation works well as can be seen from the CO_2 sensor data in Figure 4. These data indicate the excellent CO_2 sensor response without any cross-sensitivity to O_2 . There is no discernable difference between the two cycles even though the second cycle contains air which has a 20% oxygen content.

4.3 Microparticles

Testing of the inert Ru-doped reference microparticles has shown that they are sensitive to oxygen gas when outside the MTEOS matrix. The stage at which they are incorporated into the MTEOS matrix and co-immobilised with the HPTS has an effect on the response of the CO₂ sensor to oxygen. It has been found that introducing the particles into the MTEOS sol prior to hydrolysis and condensation results in a more uniform film and better sensor reproducibility within the batch.

5. Data

5.1 Screen printing:

Figure 5 shows the calibration data from oxygen sensor films screen printed onto HSPL substrate. Lines of different widths and separations were printed and the response of these films can be seen in Figure 5. The films adhere well to the substrate and the quality of the films is good. The sensitivity of the films is high at low oxygen concentrations, which suits the food packaging application. Figure 1 above shows a digital image of the screen printed films under blue LED excitation with a red filter over the camera lens.

5.2 Ink-Jet printing:

As mentioned previously, a standard ink-jet printer was used to print oxygen sensor films onto both paper and acetate. Calibration data from the ink-jet printed films is shown in Figure 6. The quality of the films is good and the process is very versatile.

In summary, optical sensors for oxygen and carbon dioxide have been developed. The indicators are immobilised in a sol-gel matrix which has many advantages i.e. ease of printability, ability to tailor the matrix to suit the particular application in particular to optimise the sensitivity of the sensor to the sensing region of interest.

The carbon dioxide indicator is a pH indicator, HPTS. Due to its short lifetime, a novel technique called DLR has been employed to enable decay-time detection in the frequency domain. The HPTS is co-immobilised in a sol-gel (MTEOS) matrix with

Ru-doped sol-gel particles. The DLR mechanism is described above and the following equation describes the mechanism

$$\cot \phi_m = \cot \phi_{\text{Ref}} + \frac{1}{\sin \phi_{\text{Ref}}} \cdot \frac{A_{\text{HPTS}}}{A_{\text{Ref}}}$$

In short the cotangent of the measured phase angle ϕ_m is linearly dependent on the amplitude ratio of the two signals, HPTS and Ru reference.

The particles are oxygen-insensitive when immobilised in the MTEOS sol-gel, and act as a reference luminophore for DLR. As for the oxygen sensor, the phase angle is measured as a function of oxygen concentration.

The detection electronics measure the variation in phase angle with oxygen or carbon dioxide concentration. The phase angle is the measured phase difference between the sinusoidally modulated reference excitation signal and the resultant fluorescence signal which is phase shifted with respect to the reference signal. The fluorescence signal changes with analyte concentration. The light sources are two light-emitting diodes, one yellow (reference which does not excite the indicators) and one blue (excitation source which excites the analyte-sensitive indicator). These light sources are modulated at 20kHz. The detector is a silicon photodiode, and the phase signals (reference and excitation) are fed into a phase detector and the phase difference is measured.

The sensor of the present invention is a fluorescence-based sensor that needs an analyser to 'read' the gas concentration [Retailers prefer that the consumer cannot determine the quality of the food, hence this is more advantageous than a visual indicator]. It is a non-invasive analyser system that can measure both oxygen and carbon dioxide, so a true indication of what is happening in the package is possible. For example, many articles and foodstuffs are packaged under modified gas atmospheres. If such a package is punctured one would expect to see a change in oxygen and carbon dioxide levels to equate with atmospheric levels and this could be determined with the sensor system of the present invention. If a package then becomes contaminated by microbes, the oxygen can be consumed by microbial growth, so it is important to have a measure of both oxygen and carbon dioxide

concentration to determine the quality of the package, hence the freshness of the food as carbon dioxide accumulation in a package headspace can be considered to be a sign of microbial growth. Overall, the invention allows the possibility of monitoring gas levels in the package over time and comparing them with standards which allows an assessment of the integrity of the package to be made.

The indicator chemistry used for the two sensors enables the use of a common light source (blue LED) and detection system, hence the analyser instrument is capable of reading both sensors.

The fact that it is a non-destructive sensor enables 100% monitoring of the packages at any stage from the packaging plant to the consumer purchase point. It could also easily be integrated into a production line.

Printing the sensors directly onto the packaging material is a distinct advantage from a consumer point of view. A European FAIR-project 'Actipak' CT 98-4170 entitled 'Evaluating safety, effectiveness, economic-environmental impact and consumer acceptance of active and intelligent packaging' found that in Europe, consumers were negative about separate pouches or objects included in packaging. Their main concerns were that sachets would break or that accidental injection would occur. By printing the sensors onto the packaging material, they can be largely 'invisible' to consumers if necessary. Sensors are printed onto the packaging material and not onto an adhesive or sticker and so are more secure.

The words "comprises/comprising" and the words "having/including" when used herein with reference to the present invention are used to specify the presence of stated features, integers, steps or components but does not preclude the presence or addition of one or more other features, integers, steps, components or groups thereof.

Claims

1. A CO₂ sensor comprising a pH indicator and a long-lived reference luminophore which are co-immobilised in a porous sol-gel matrix.
- 5 2. A CO₂ sensor as claimed in claim 1 wherein the pH indicator is selected from the group consisting pH indicators including hydroxypyrene trisulphonate (HPTS), fluorescein, m-cresol purple, thymol blue, phenol red, xylenol blue.
- 10 3. A CO₂ sensor as claimed in claim 1 or 2 wherein the long-lived reference luminophore is selected from the group consisting of ruthenium-doped sol-gel microparticles in particular [Ru^{II}-tris(4,7-diphenyl-1,10-phenanthroline)]Cl₂-doped microparticles, ruthenium-based compounds with α -diimine ligands, luminescent transition metal complexes with platinum metals Ru, Os, Pt, Ir, Re or Rh as the central metal atom and with α -diimine ligands, and phosphorescent porphyrins with Pt or Pd as the central metal atom.
- 15 4. A CO₂ sensor as claimed in any preceding claim wherein the porous sol-gel matrix is selected from the group consisting of a methyltriethoxysilane (MTEOS) sol-gel matrix, hybrid (organic-inorganic) sol-gel matrices including ethyltriethoxysilane (ETEOS), phenyltriethoxysilane (PhTEOS) and methyltrimethoxysilane (MTMS).
- 20 5. A combined O₂ /CO₂ sensor comprising:-
 - (a) an O₂ sensor comprising an oxygen sensitive ruthenium complex immobilised in a porous sol-gel matrix, and
 - (b) an CO₂ sensor comprising a pH indicator and a long-lived reference luminophore which are co-immobilised in a porous sol-gel matrix.
- 25 6. A combined O₂ / CO₂ sensor as claimed in claim 5 wherein the ruthenium-complex is selected from the group consisting of ruthenium-based compounds with α -diimine ligands and luminescent transition metal complexes with platinum metals (Ru, Os, Pt, Ir, Re or Rh) as the central metal atom and with α -diimine ligands, and phosphorescent porphyrins with Pt or Pd as the central metal atom.
- 30

7. A combined O₂ / CO₂ sensor as claimed in claim 5 or claim 6 wherein the immobilised O₂ sensor and the immobilised CO₂ sensor are coated onto the same substrate.

5

8. A combined O₂ / CO₂ sensor as claimed in claim 5, 6 or 7 wherein the two sensors are coated onto the substrate side-by-side.

9. A combined O₂ / CO₂ sensor as claimed in any of claims 5 to 8 wherein the substrate is selected from the group consisting of a layer of plastics material, including surface-enhanced PET and PET/PE laminates, glass, rigid substrate materials including Perspex/PMMA, polycarbonate, and flexible substrate materials including acetate or flexible polymer materials.

10

10. A method of making a CO₂ sensor comprising :-

15

(1) synthesis of an Ru(dpp)₃(TSPS)₂ ion-pair comprising mixing dissolved Ru(dpp)₃Cl₂ with trimethylsilylpropane sulfonic acid, sodium salt and allowing the ion-pair to precipitate,

20

(2) synthesis of the particles comprising condensing the dissolved Ru(dpp)₃(TSPS)₂ ion-pair with TEOS and halting the condensation reaction with alcohol, washing the condensate with alcohol and drying the condensate, and

25

(3) and fabrication of the CO₂ sensor films comprising suspending the doped reference particles in the coimmobilisation matrix solution, mixing the coimmobilisation matrix solution into a pH indicator solution which comprises a pH indicator in a quaternary ammonium hydroxide solution, and saturating the mixture immediately with CO₂ followed by deposition onto a substrate.

30

11. A method as claimed in claim 10 wherein the quaternary ammonium hydroxide is selected from the group consisting of cetyl-trimethyl ammonium hydroxide (CTA-OH), tetra-octyl ammonium hydroxide (TOA-OH) or tetra-butyl ammonium hydroxide (TBA-OH) or other quaternary ammonium hydroxides.

12. A method as claimed in claim 10 or 11 wherein the pH indicator is selected from the group consisting pH indicators including hydroxypyrene trisulphonate (HPTS), fluorescein, m-cresol purple, thymol blue, phenol red, xyleneol blue.
- 5 13. A packaging medium having a combined CO₂ sensor and an O₂ sensor as claimed in any of claims 5 to 9 formed on a surface of the medium which will lie internally of the package when the package is formed.
- 10 14. A packaging medium as claimed in claim 13 wherein the sensors are formed on the packaging medium by a method selected from the group consisting of dip-coating, spin-coating, spray-coating, stamp-printing, screen-printing, ink-jet printing or gravure printing.
- 15 15. A quality control method comprising reading a combined O₂ / CO₂ sensor as claimed in any of claims 5 to 9, formed on the internal surface of a package, with an optical reader, and determining the levels of O₂ and CO₂ inside the package in relation to a control, a rise in O₂ level and a corresponding fall in CO₂ level indicating contamination of the package.
- 20 16. A method of screen-printing a combined O₂ /CO₂ sensor as claimed in any of claims 5 to 9 onto a plastics substrate comprising forcing the sensor sol through a mask or mesh and drying the substrate.
- 25 17. A method of ink-jet printing a combined O₂ /CO₂ sensor as claimed in any of claims 5 to 9 onto a plastics substrate comprising filling an ink-jet printer cartridge with sensor sol and printing the sensor sol onto the substrate using an ink-jet printer.

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Figure 1

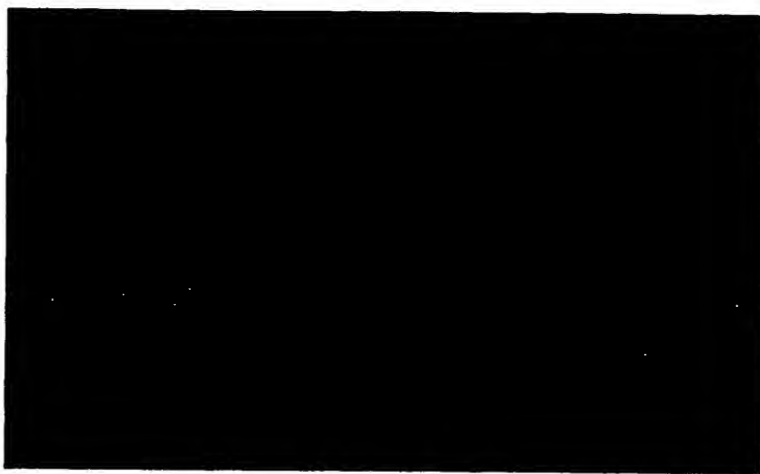


Figure 2

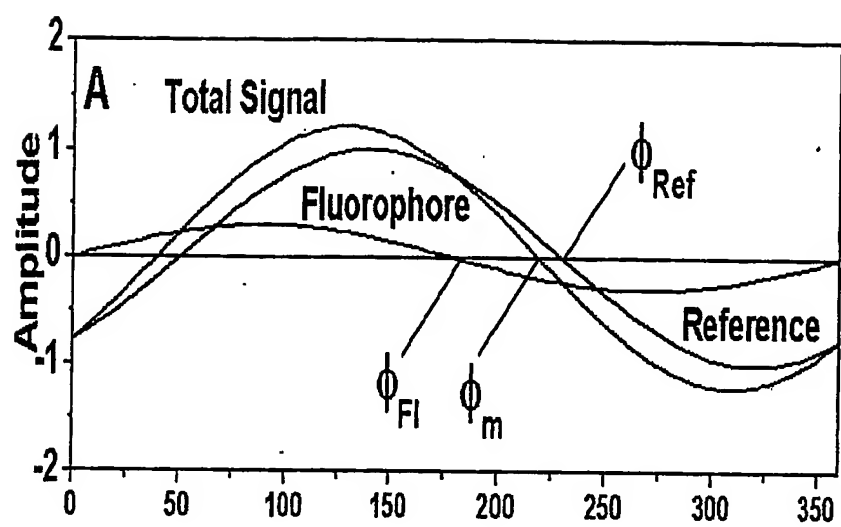


Figure 3

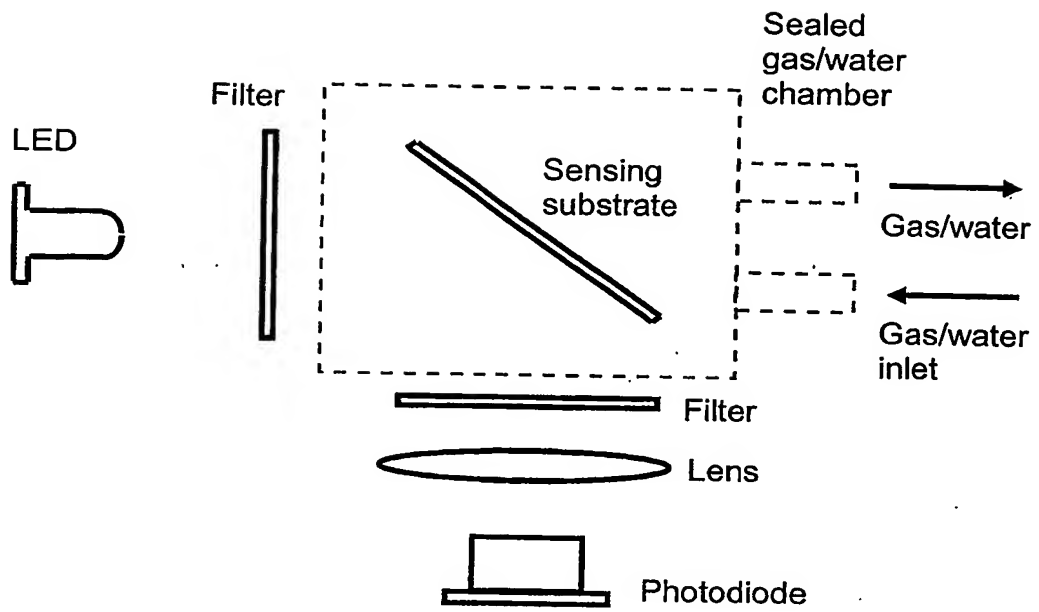


Figure 4

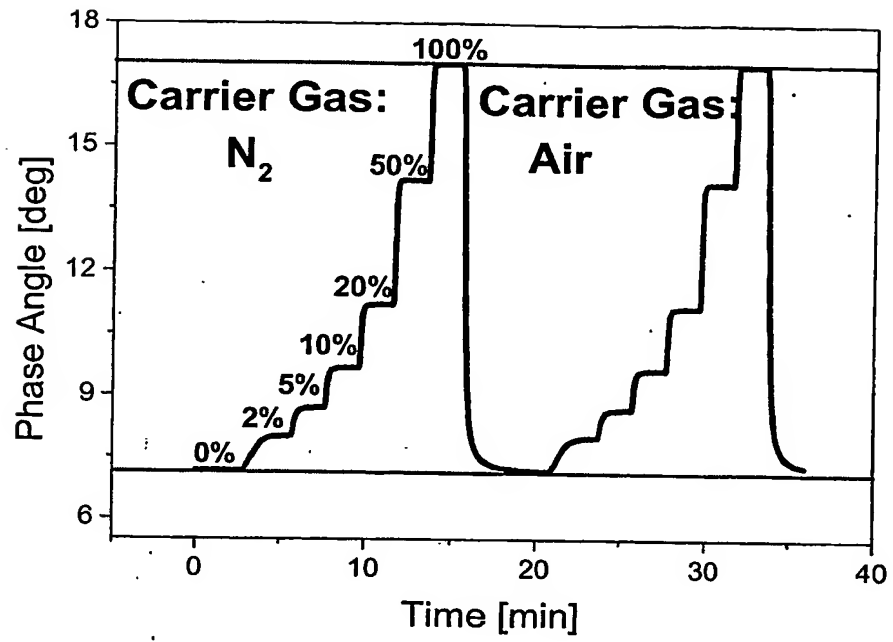


Figure 1 is a line graph showing the phase angle (deg) on the y-axis (ranging from 20 to 40) versus time (min) on the x-axis (ranging from -2 to 20). The graph displays the phase angle response of a 5 mm thick sample to a stepwise increase in oxygen concentration from 0% to 100% O₂. The phase angle decreases in discrete steps as the oxygen concentration increases. The steps occur at approximately 2, 4, 6, 8, 10, 12, 14, and 16 minutes. The phase angle starts at approximately 38.5 degrees at 0% O₂ and drops to approximately 20.5 degrees at 100% O₂. The graph also shows the phase angle for 3 mm, 7 mm, and 1 mm thick samples, which follow a similar trend but with slightly different values.

Time (min)	0% O ₂	2% O ₂	5% O ₂	10% O ₂	20% O ₂	50% O ₂	100% O ₂
0	38.5						
2		38.5					
4			38.5				
6				38.5			
8					38.5		
10						38.5	
12							38.5
14							
16							38.5
18							
20							

Figure 6

